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Nuclear spins of neutron-deficient polonium isotopes

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With 7 figures in the text

ABSTRACT

The atomic-beam magnetic resonance method has been used to measure the spin-values of neutron-deficient polonium isotopes with the following results:

Mass number	Half-life	Spin
201	18 m	3/2
202	43 m	0
203	42 m	5/2
204	3.6 h	0
205	1.8 h	5/2
206	8.8 d	0
207	5.7 h	5/2

and the atomic g-factor of polonium $g_J = 1.39609 \pm 0.00004$.

There is some uncertainty as to the spin 0 assignments. For very small hfs, the resonance frequencies for spins other than zero are nearly identical to the transition frequency for spin 0. For that reason we have calculated an upper limit for the magnetic dipole interaction constant under the assumption that the spin is one.

I. Introduction

The nuclear ground-state spins of neutron-deficient isotopes in the nuclear lead region have been studied earlier by the atomic-beam group at Uppsala [1, 2, 3, 4], and several unexpected results have been obtained. Among these are the extremely low value of the magnetic moment of Tl^{198} and the spin value of Bi^{200}. These isotopes have the same number of neutrons as Po^{201}, the spin of which is therefore of great interest. As the Z value of polonium is even, the comparison of the spin-values with the nuclear shell model is very easy, and a systematic investigation is well justified.

II. The method

For an atom in an external magnetic field B the Hamiltonian can be written as

$$\mathcal{H} = g_J \mu_0 \mathbf{J} \cdot \mathbf{B} + g_I \mu_0 \mathbf{I} \cdot \mathbf{B} + h a \mathbf{I} \cdot \mathbf{J} + \text{higher order interactions}, \tag{1}$$

where $$g_J = -\mu_J/J\,\mu_0, \text{ and } g_I = -\mu_I/I\,\mu_0.$$

In a low field $\mathcal{H}$ is diagonal in an (F, m) representation and the energy becomes

$$(F, m\,|\mathcal{H}|\,F, m) = g_J\,\mu_0\,B\,\frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)}\,m$$

$$+\,g_I\,\mu_0\,B\,\frac{F(F+1)+I(I+1)-J(J+1)}{2F(F+1)}\,m + \frac{h\,a}{2}\,[F(F+1)-I(I+1)-J(J+1)], \quad (2)$$

whereas in a high field it is diagonal in an (m_I, m_J) representation and the energy becomes

$$(m_I, m_J\,|\mathcal{H}|\,m_I, m_J) = g_J\,\mu_0\,B\,m_J + g_I\,\mu_0\,B\,m_I + h\,a\,m_I\,m_J. \quad (3)$$

For intermediate fields the energies can be obtained by the application of perturbation theory. For spin measurements only the first term in (2) has to be taken into account, and the transition frequency is given by the following formula:

$$\nu = \frac{\mu_0\,B}{h}\,g_J\,\frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)}. \quad (4)$$

Now, this is the frequency for an ordinary Zeeman transition ($\Delta m = 1$), and though Lindgren [5] has shown how the apparatus used could be changed to detect such transitions for even Z elements, we found it more convenient to use multiple quantum transitions with $\Delta m \geqslant 2$. These are easy to observe, and according to Kusch [6] and Salwen [7] they can be induced with a comparatively low amount of radio frequency power of the same frequency as a single quantum transition ($\Delta m = 1$).

The electronic configuration of polonium is p^4 and the ground state is a mixture of ${}^3P_2$ and ${}^1D_2$. Optical measurements performed by G. W. Charles *et al.* [8] and calculations by S. Mrozowski [9] have given the following values of the electrostatic and spin-orbit interaction constants: $F_2 = 1096$ K, $\zeta = 12379$ K. Using a method described by Inglis and Johnson [10] and Condon and Shortley [11] we have calculated the g_J-value to be 1.3973, which value includes neither the Schwinger, the Breit-Margenau, nor the diamagnetic corrections, which probably amount to a few per mille.

For non-zero spin values two Zeeman transitions can be observed, namely

$$(F, m) = (F, -F+3) \leftrightarrow (F, -F+1),$$

where $F = I + J$ or $I + J - 1$. The beam detection is accomplished by measuring the radioactivity of the atoms collected on a foil. The decay curves are analysed to identify the isotopes giving the different resonance signals. The half-lives for all the isotopes examined have been reported earlier [12, 13, 14, 15, 16]. The fact that even A isotopes have integral spin values while odd A isotopes have half-integral spins facilitated the identification.

III. Experimental procedure

The experiments have been made with the six-pole focusing atomic-beam magnetic resonance apparatus at Uppsala, which has been described earlier [3, 4, 5]. The polonium isotopes were produced by (p, kn) reactions on bismuth in the synchrocyclotron at the Gustaf Werner Institute at Uppsala. The proton energies ranged from 50 to 110 MeV, the bombarding times from $\frac{1}{2}$ to 2 hours. Two different target materials were used, Bi and Bi_2O_3. Working with the more short-lived isotopes, Po^{201}, Po^{202}, and Po^{203}, a rapid chemical separation was essential and Bi_2O_3 was used. The separation was accomplished by plating the polonium on silver wires by internal electrolysis in a hot solution of the target in 6 N hydrochloric acid. This solution can be obtained directly with Bi_2O_3. Metallic bismuth, on the other hand, has to be dissolved in nitric acid after which hydrochloric acid has to be added and boiled away several times, till no nitric acid is left. Starting with Bi_2O_3, a yield of about 50 per cent could be obtained in 15 minutes [13].

As polonium will probably evaporate as molecules at the oven temperatures used (500°–600°C), the oven was given a special design. It was of the type described by Lindgren *et al.* [3] with a long channel which was heated by electron bombardment to produce a great thermal gradient along the oven. Molecules hitting the channel walls will then be thermally dissociated. The oven material was molybdenum, and though no carrier material was added, a steady beam was obtained for several hours. Detection was effected with carbon-coated copper foils, and the radioactivity was measured with scintillation counters, equipped with thin NaI chrystals, detecting the X-rays following electron capture decay. All resonance lines were observed in at least three different magnetic fields in the range 0.7–3 gauss to check the linearity.

IV. Results

The first resonances obtained indicated that isotopes with spin values 0 and 5/2 were present in a beam mainly consisting of Po^{204}, Po^{205}, and Po^{206}. To measure the g_J-value we followed the spin 0 signal into stronger fields and as the frequency varied linearly with the field, we could compute the g_J-value (Table 1). The result, 1.39609 ± 0.00004, is in good agreement with the theoretical value (see above). Again we searched for different spins at weak fields, using samples of different isotopic composition. The decay curves of the signals have been analysed, and since most isotopes have radioactive daughters, the analysis is quite complex (Fig. 1–5). Nevertheless we can assign the following spin values: 18 m Po^{201} $I = 3/2$, 42 m Po^{203} $I = 5/2$, 1.8 h Po^{205} $I = 5/2$, and 5.7 h Po^{207} $I = 5/2$. Further, it is very probable that 43 m Po^{202}, 3.6 h Po^{204}, and 8.8 d Po^{206} have the spin 0; however, there is some uncertainty.

The resonances corresponding to the spin 0 can also be due to a non-zero spin, provided the hyperfine structure separations are very small. Assuming that the spin is one and that the hfs is entirely due to magnetic dipole interaction, we get the transition frequencies from (3):

$$\nu = \frac{\mu_0 B}{h} g_J + X,$$

where $X = -a, -a/2, 0, a/2$, or a. Here the g_I-term is excluded and we assume a two-quantum transition for which $\Delta m_J = 2$, $\Delta m_I = 0, \pm 1$. As only one resonance line is

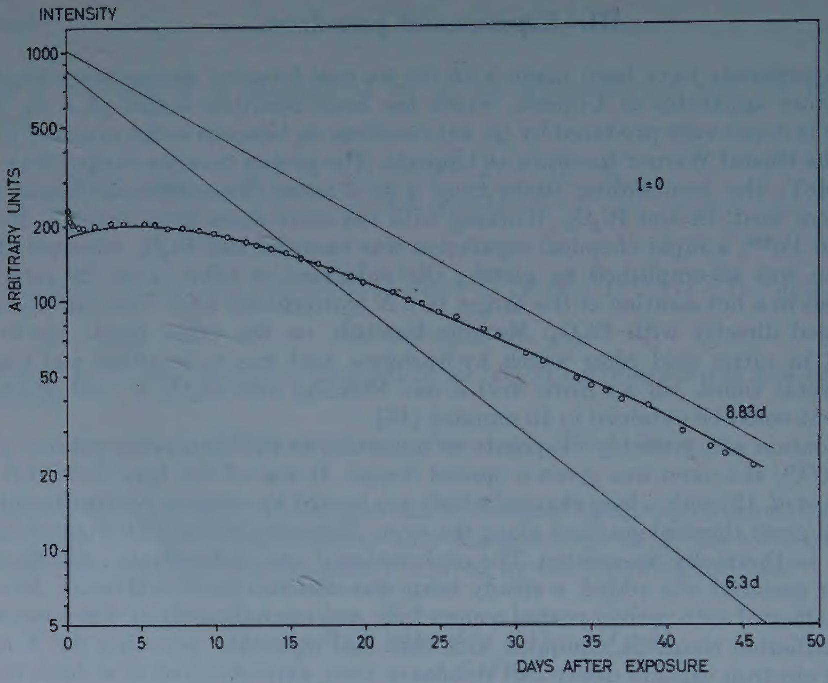

Fig. 1. Decay curve of a spin 0 signal analysed into a (8.83 + 6.3) d activity. The sample from a 2 h bombardment of Bi with 50 MeV protons.

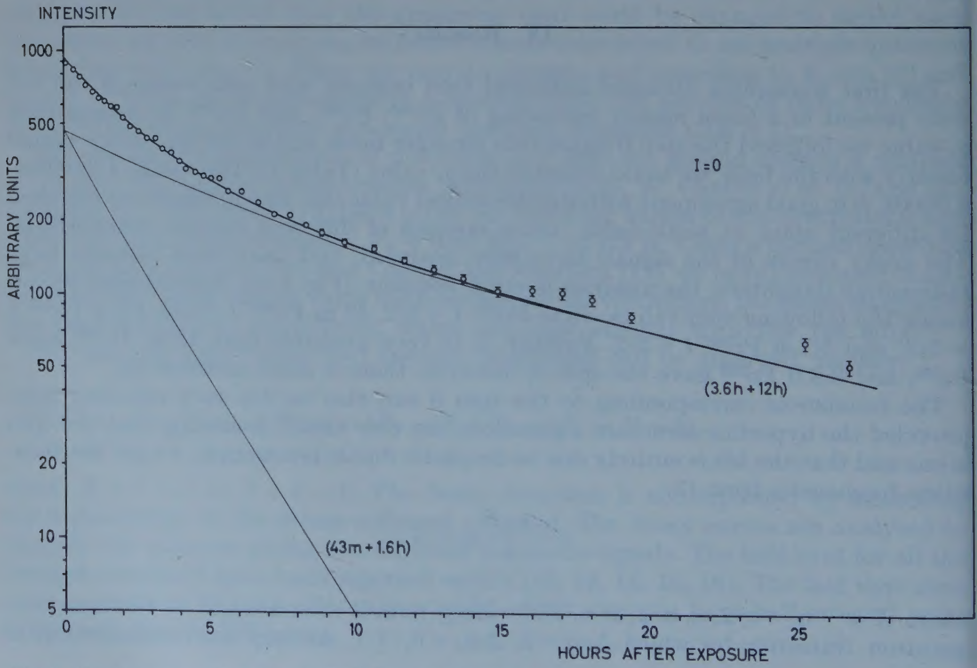

Fig. 2. Decay curve of a spin 0 signal analysed into a 43 m + 1.6 h and a (3.6 + 12) h activity. The sample from a 2 h bombardment of Bi_2O_3 with 95 MeV protons.

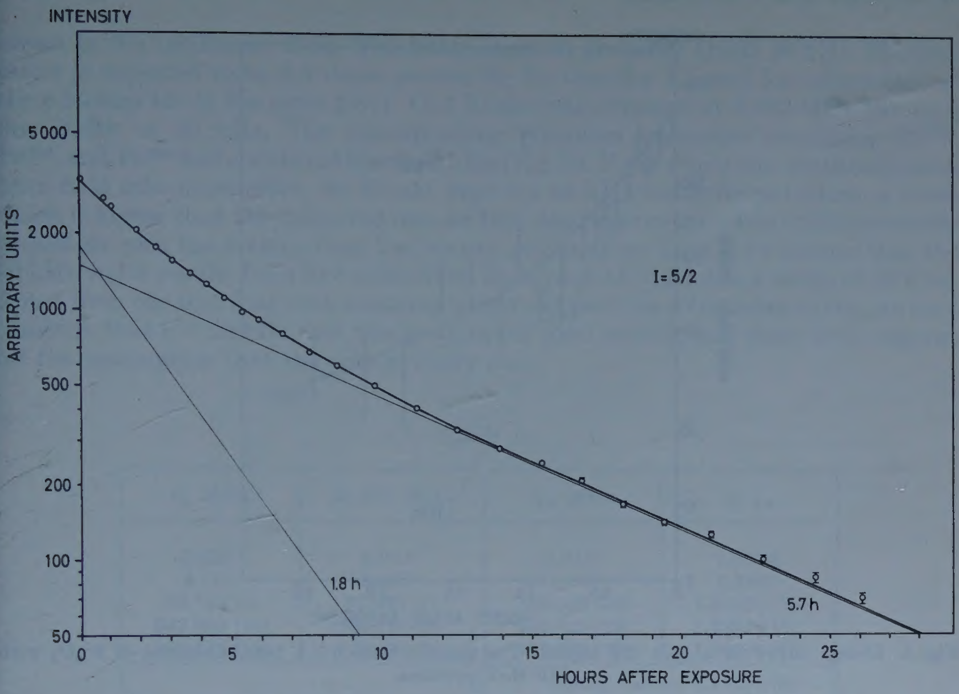

Fig. 3. Decay curve of a spin 5/2 signal analysed into a 1.8 h and a 5.7 h activity. The sample from a 2 h bombardment of Bi with 50 MeV protons.

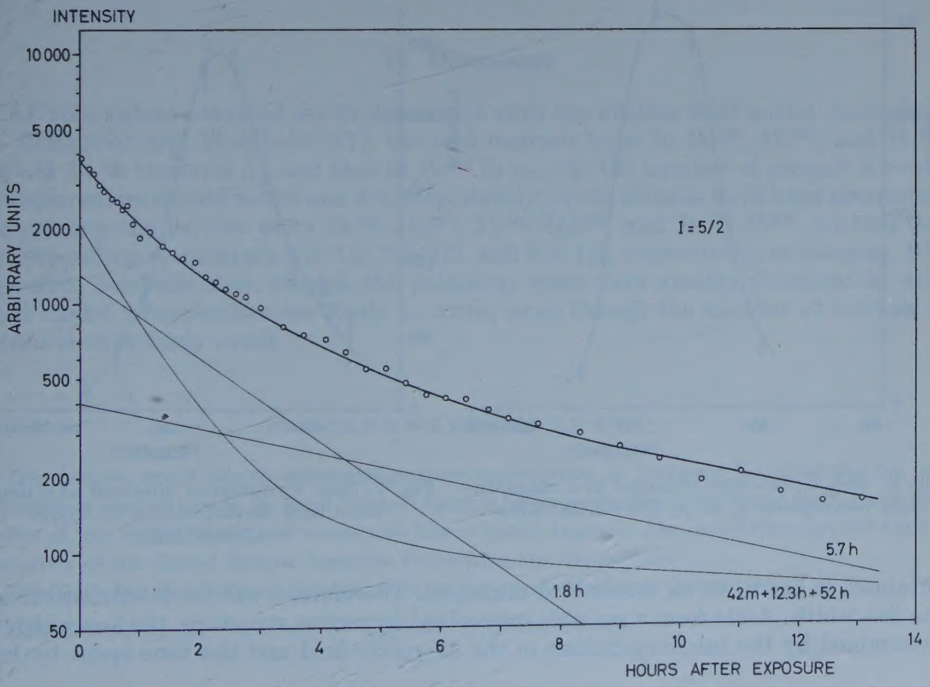

Fig. 4. Decay curve of a spin 5/2 signal analysed into a 42 m + 12.3 h + 52 h, a 1.8 h, and a 5.7 h activity. The sample from a 1 h bombardment of Bi with 100 MeV protons.

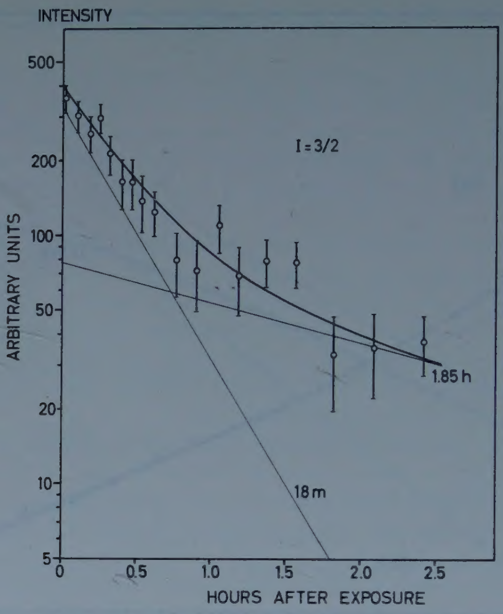

Fig. 5. Decay curve of a spin 3/2 signal. The sample from 0.5 h bombardment of Bi_2O_3 with 110 MeV protons.

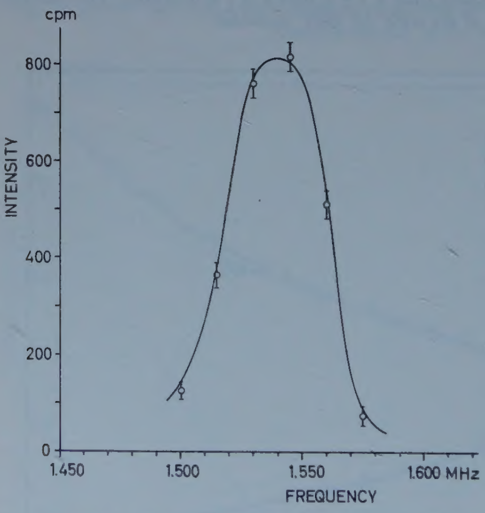

Fig. 6. Spin 0 resonance obtained at a magnetic field corresponding to $\mu_0 B/h = 1.100$ MHz.

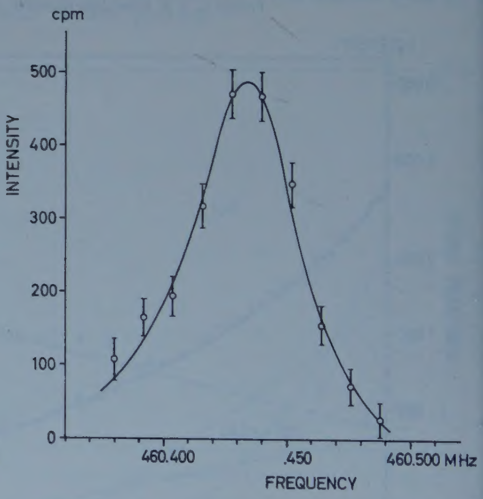

Fig. 7. Spin 0 resonance obtained at a magnetic field corresponding to $\mu_0 B/h = 329.809$ MHz.

obtained, it has to be an unresolved multiplet. Therefore, *a* can be determined from the line width. Aside from a possible unresolved hyperfine structure, the line width is determined by the inhomogeneities in the magnetic field and the time spent by the atoms in the oscillatory field. The latter effect is probably about 20 kHz. The first factor is expected to be 2.8 times greater for Po than for K, used for calibration, as the g-factors are in the ratio 2.8:1. One K line was obtained at 0.552 MHz having a line width of 30 kHz. The corresponding polonium resonance containing Po^{202}, Po^{204}, and Po^{206} had a width of about 50 kHz (Fig. 6). If the whole line width originates from field inhomogeneities, we should expect a 85 kHz width for polonium, a value which is higher than the measured one. In fact, the experimental line width is entirely consistent with the a-value zero, but we can get an upper limit if we assume that the 50 kHz width results from five unresolved lines, each of which has a width of 20 kHz. Apart from the fact that such a mixing would not produce a Gaussian curve, we may conclude that $a < 20$ kHz, but this is an upper limit indeed, and there is no support for the assumption that the spin is really one.

Table 1.

ν_k MHz	$\mu_0 B/h$ MHz	ν_{Po} MHz	$g_{J,\,Po}$
2.035	4.014	5.613	1.3984
4.110	8.000	11.168	1.3960
69.757 (5)	99.993 (7)	139.620 (30)	1.39630 (32)
393.065 (15)	330.000 (9)	460.725 (20)	1.39614 (8)
392.732 (15)	329.809 (9)	460.434 (10)	1.39606 (5)
		Mean value:	1.39609 (4)

Errors in the last significant digits are enclosed in parentheses.

V. Discussion

All spin values obtained are in agreement with the nuclear shell model. According to Blomqvist and Wahlborn [17], the odd neutron holes in Po^{207}, Po^{205}, and Po^{203} should be in the level $f_{5/2}$ and that of Po^{201} in $p_{3/2}$. As the number of protons is even, the spin values should be 5/2 and 3/2, respectively, or the same as have been measured. Examining the isotone pairs Po^{205}–Hg^{201}, Po^{203}–Hg^{199}, and Po^{201}–Pt^{195}, we find the corresponding spin-values 5/2–3/2, 5/2–1/2, and 3/2–1/2, respectively, to disagree. We therefore conclude that, though the polonium spins were exactly predicted by the shell model, irregularities are likely to occur, even though the number of holes in a closed shell is fairly small.

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